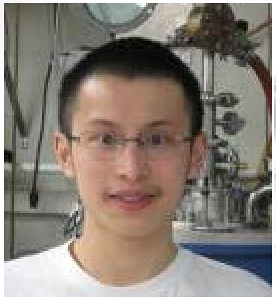
Evidence for the chiral anomaly in a Dirac Semi-metal


Jun Xiong


S. Kushwaha


Tian Liang


Jason Krizan


Quinn Gibson

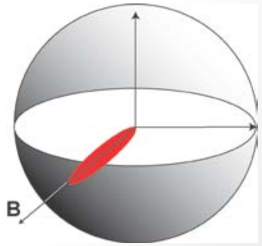

Bob Cava


NPO

Jun Xiong, Tian Liang, Minhao Liu, Max Hirschberger, Wudi Wang, N. P. Ong
Department of Physics, Princeton Univ.

Satya Kushwaha, Quinn Gibson, Jason Krizan, Maz Ali, R. J. Cava
Department of Chemistry, Princeton Univ.

1. **Introduction to Dirac semimetals**
2. **Ultrahigh mobilities and giant MR in Cd_3As_2**
3. **Intro to Weyl physics**
4. **Chiral anomaly in Na_3Bi**

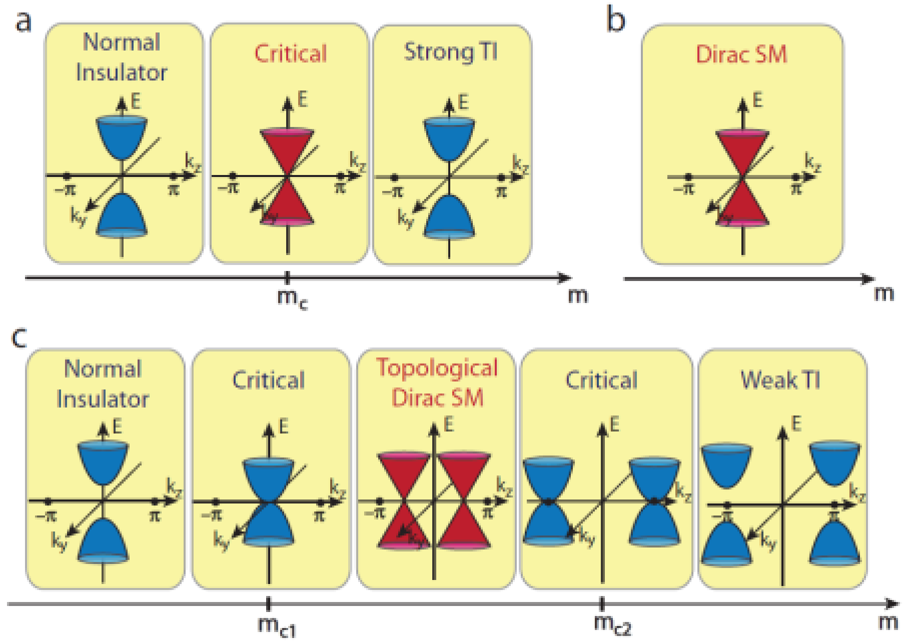


Supported by MURI, ARO, NSF (MRSEC), Moore Foundation

Dirac node protection by Point-Group Symmetry

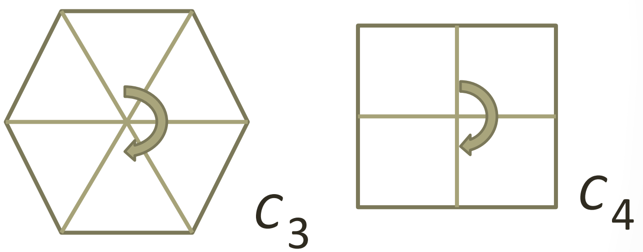
Wan, Turner, Vishwanath, Savrasov, *PRB* 2011
Young, Kane, Mele et al. *PRL* 2012
Wang, Dai et al., *PRB* 2012
Fang, Gilbert, Dai, Bernevig, *PRL* 2012

unstable



Nodes stable

B.J. Yang and N. Nagaosa, arXiv 1404.0754



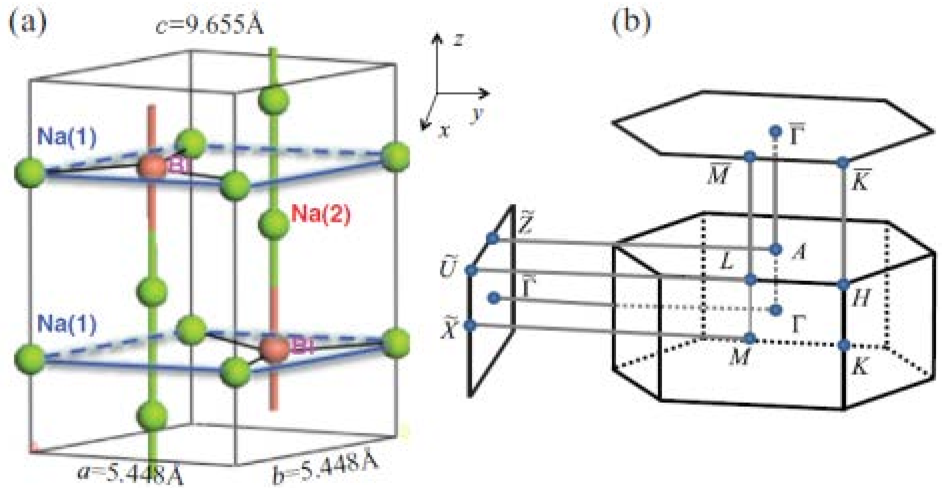
Initial idea: Dirac node is protected by TRS and IS if *pinned* to zone corners.

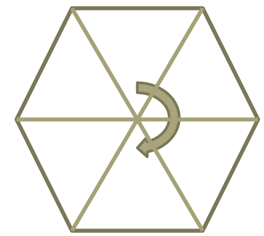
Later, inclusion of point-group symmetry C_n extends protection to *anywhere* on symmetry axis.

Protected Dirac nodes in semimetal Na_3Bi

Wang, Dai, Fang et al. *PRB* 2012
Wang, Dai, Fang et al. *PRB* 2013

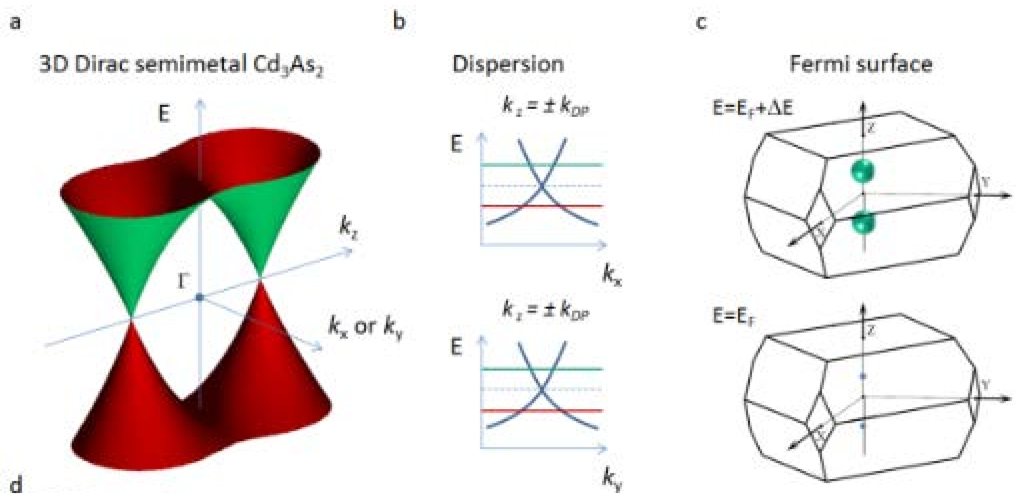
Na_3Bi

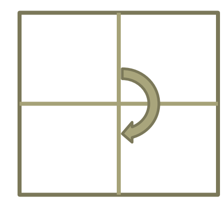




C_3

Cd_3AS_2





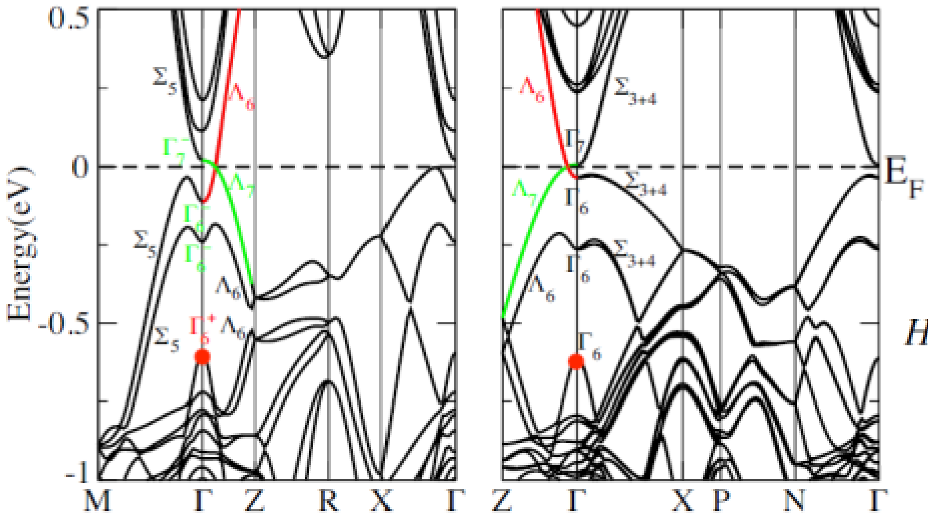
C_4

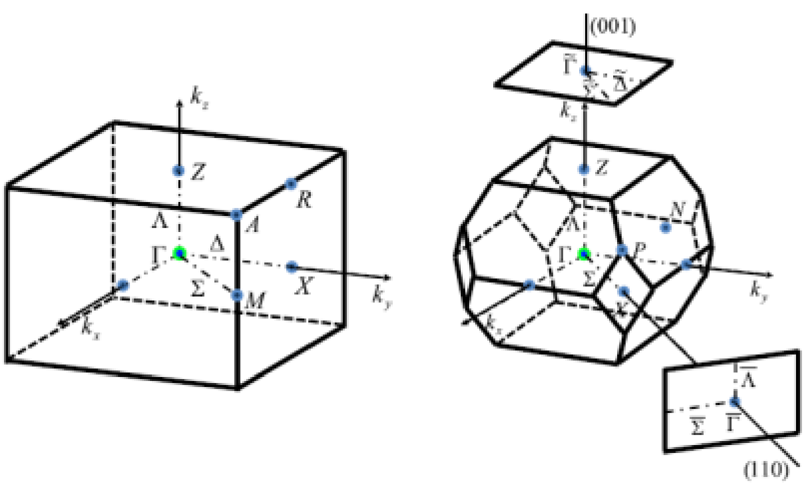
Three Dimensional Dirac Semimetal and Quantum Spin Hall Effect in Cd_3As_2

Zhijun Wang, Hongming Weng,* Quansheng Wu, Xi Dai, and Zhong Fang†

IOP, Beijing

Point Group C4





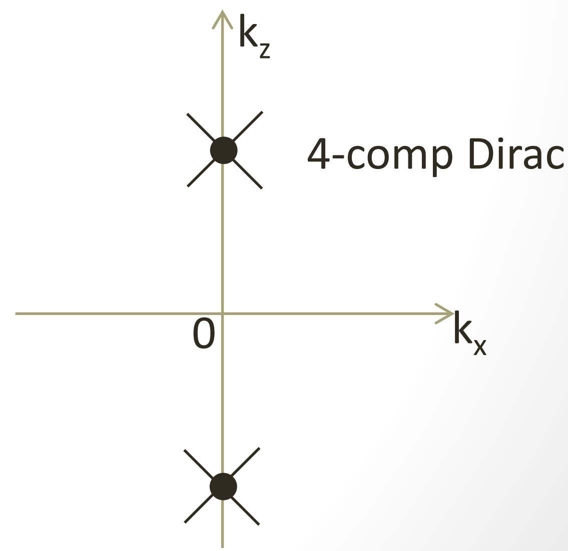
(a) structure I

(b) structure II

4x4 basis set

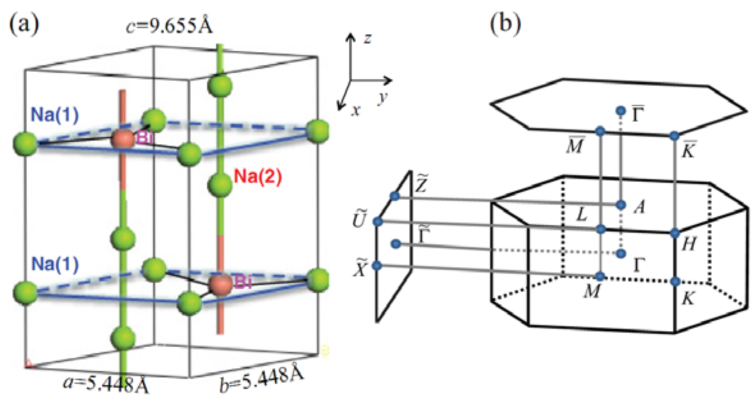
$|S,½\rangle$, $|P,3/2\rangle$, $|S,-½\rangle$, $|P,-3/2\rangle$

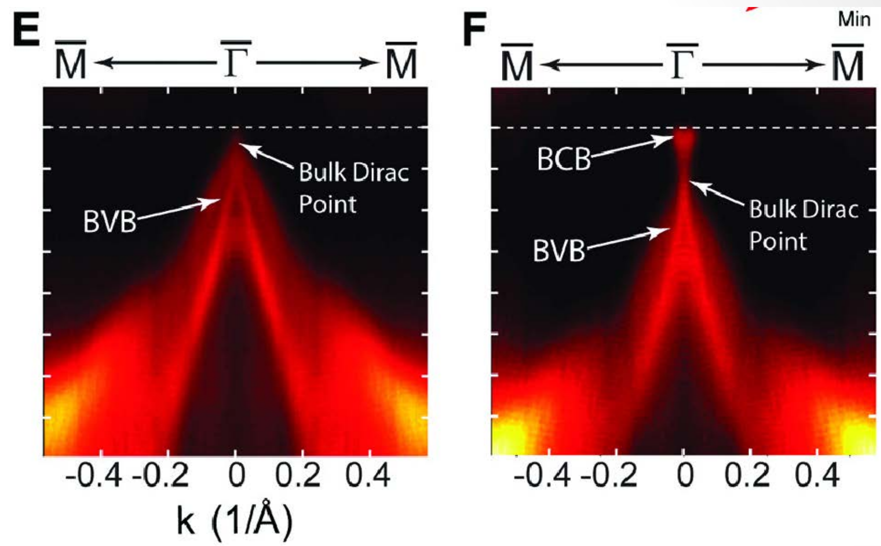
$$H_\Gamma(\mathbf{k}) = \epsilon_0(\mathbf{k}) + \begin{pmatrix} M(\mathbf{k}) & Ak_+ & 0 & B^*(\mathbf{k}) \\ Ak_- & -M(\mathbf{k}) & B^*(\mathbf{k}) & 0 \\ 0 & B(\mathbf{k}) & M(\mathbf{k}) & -Ak_- \\ B(\mathbf{k}) & 0 & -Ak_+ & -M(\mathbf{k}) \end{pmatrix},$$



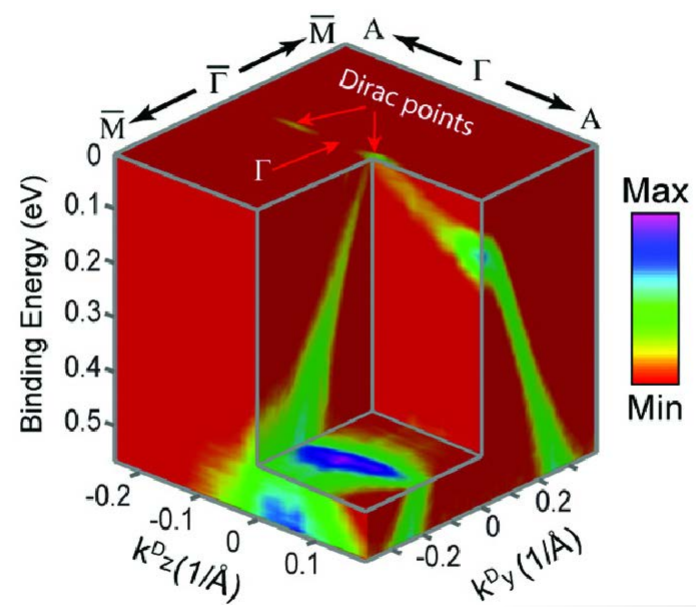
Photoemission on Na_3Bi and Cd_3As_2

Point group C3



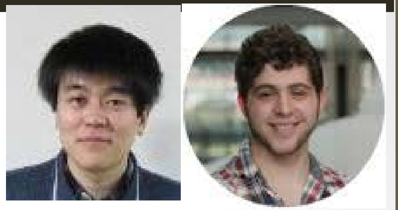


Liu, Chen *et al*, *Science* 2014
Neupane, Hasan et al., *Nat Comm.* 2014
Borisenko, Cava et al., *PRL* 2014

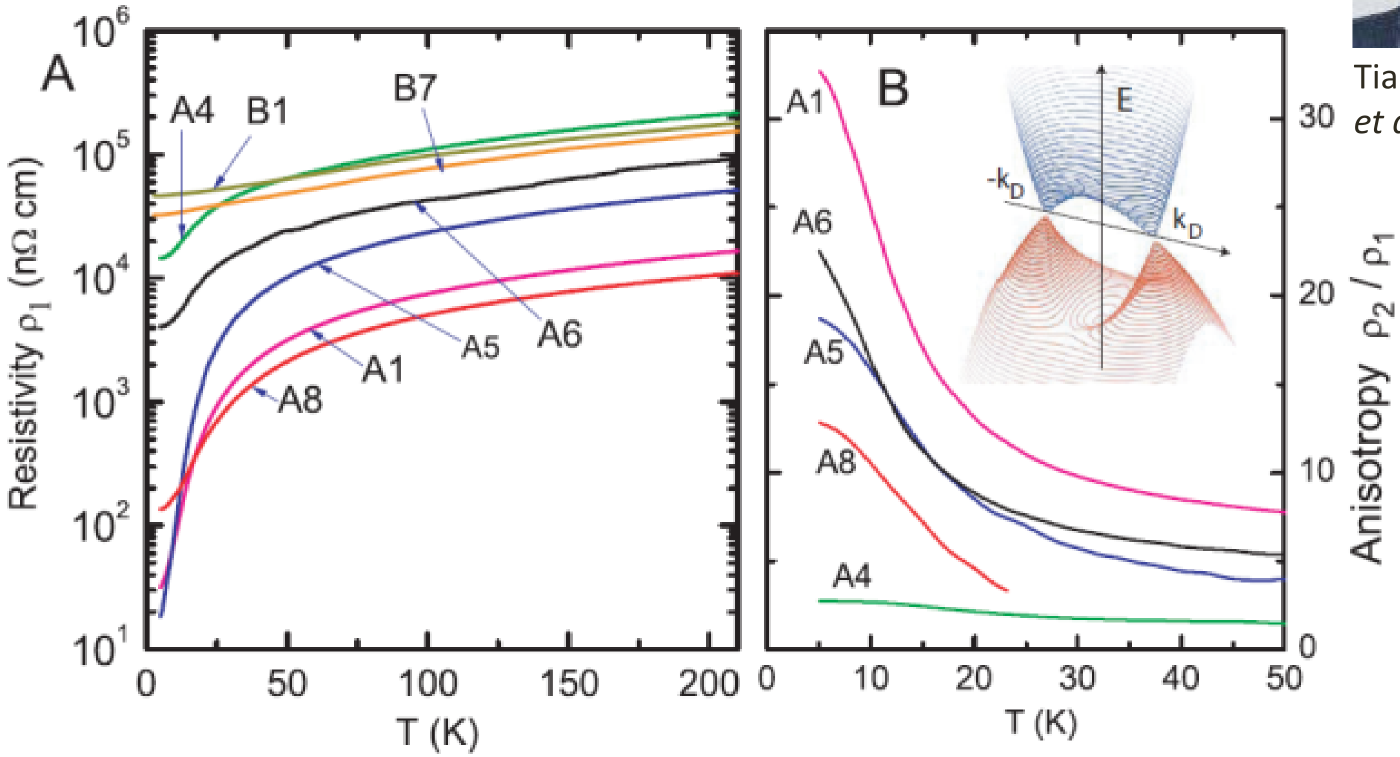


$V_x \approx V_y = 3.74\times10^5$ m/s, $V_z = 2.89\times10^4$ m/s

Cd3As2 Resistivity vs. Temperature --- RRR shows huge variation



Tian Liang, Quinn Gibson, *et al*. Nat. Mater. 2015



Set A (crystals) show 1000 fold difference in RRR.

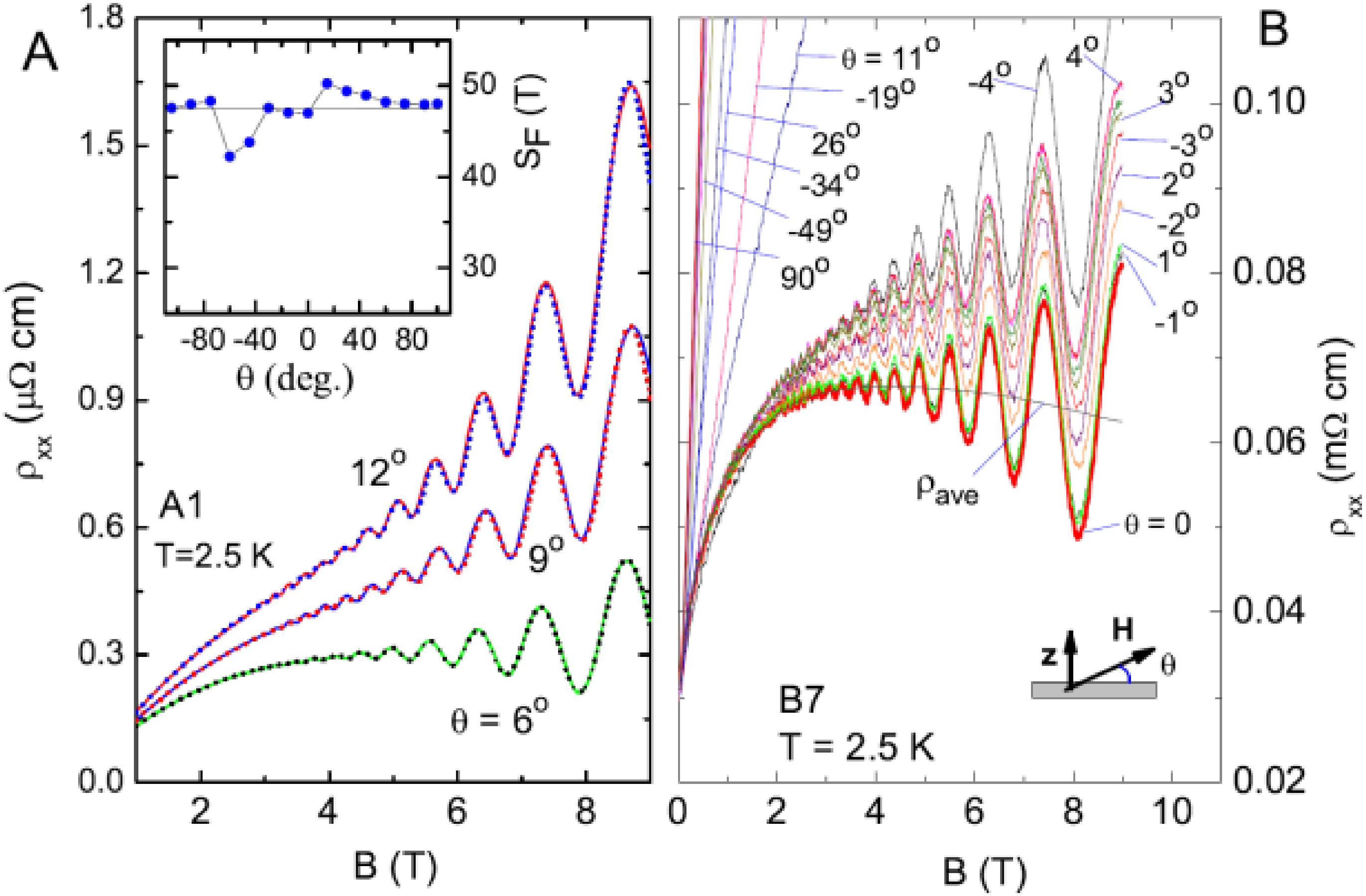
Some crystals show very low residual resistivity 20 nΩcm

Correlated with large resistivity anisotropy (30)

Set B samples have higher resistivity

Shubnikov de Haas oscillations (Set B)

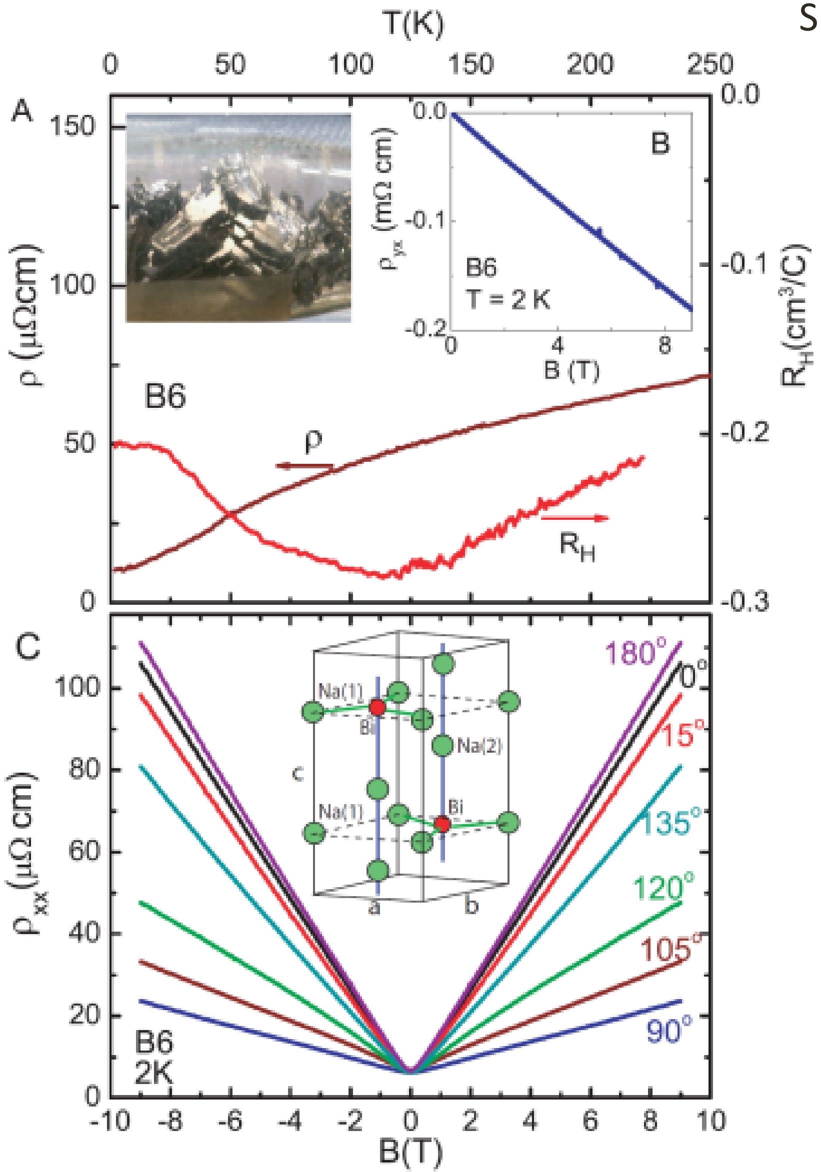
Tian Liang, Quinn Gibson *et al*. Nat. Mater. 2015



Chiral anomaly?

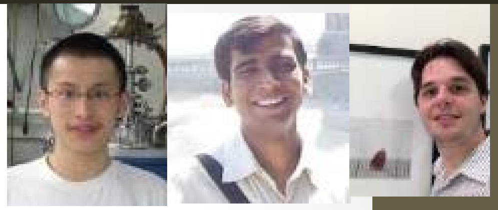
Negative, longitudinal MR detected at $\theta = 0^\circ$, but swamped by positive MR term (E_F is much too high).

Transport results on Na_3Bi



S. Kushwaha *et al.*, *APL* 2015

Jun Xiong *et al.*, submitd



Deep purple crystals

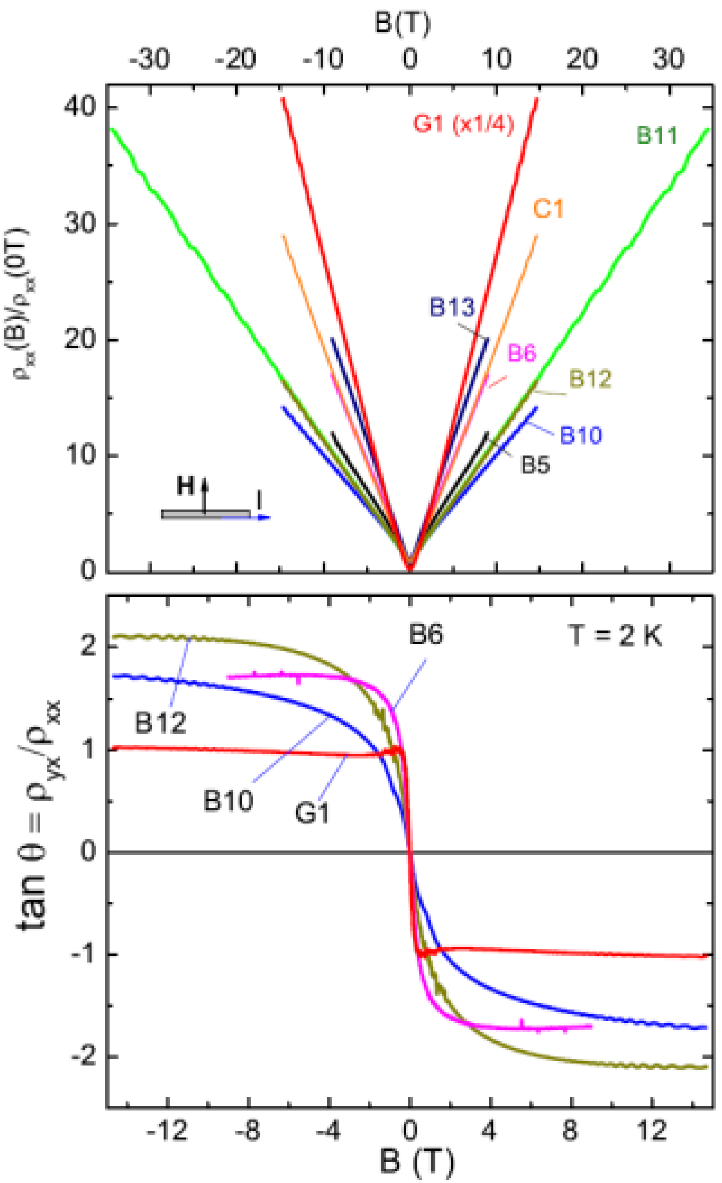
Rapidly oxidized in ambient air (30 s)

Large linear MR similar to Set B Cd_3As_2 samples

E_F 400 mV above node

H-linear MR and step-profile of Hall angle tan θ_H

Jun Xiong et al., PRL submitd



Conventional

$\rho_{xx}(B) \sim [1+(\mu B)^2]$

$\tan\theta_H \sim \mu B$

In Na_3Bi

$\rho_{xx}(B) \sim B$, linear MR

$\tan\theta_H$ has a *step-function* profile

Dirac node, Weyl nodes and Chiral Anomaly

Breaking Time Reversal symmetry in magnetic field

Search for Weyl physics

Chiral anomaly and axial current

Recent reports of Negative Longit MR in semimetals

1. Neg. longit. MR in $Bi_{1-x}Sb_x$, Li et al., PRL 2013 --- Accidl band x'ing

2. Neg. longit MR in Cd_3As_2, Tian Liang et al., Nat Mat. 2015 --- Dirac SM

3. Neg. longit. MR in $ZrTe_5$, Brookhaven Nat. Lab. arXiv --- QSHE?

4. Neg. longit. MR in $PdCoO_2$, Balicas, Maeno, Hussey et al. arXiv --- ??

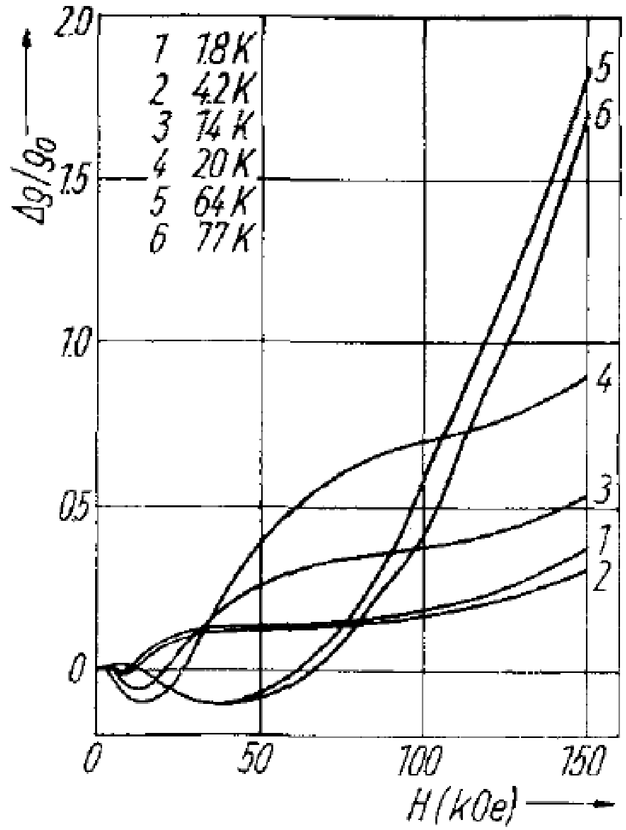
5. Neg. longit. MR in TaAs, NbAs, S. Jia and Hasan, arXiv -- Weyl metals

A very old system

6. CdxHg1-xTe, Tsdidilkovskii et al., Phys. Stat. Sol. (1974)

A very early report of negative longitud. MR in CdHgTe

Tsdidilkovskii, Giriat, Kharus, Neifeld, Phys. Stat. Sol. 64, 717 (1974)



A negative longit. MR is not restricted to chiral anomaly

Chiral anomaly in Quantum Field Theory

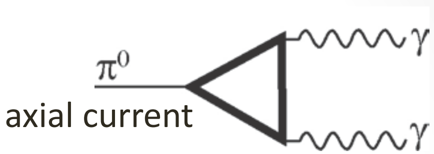
Intro to QFT, Peskin Schroeder
QFT in a Nutshell, Tony Zee

1969 Charged pions decay leptonically, $\pi^+ \rightarrow \mu^+ + \nu$
But, neutral pion decays electromagnetically

$$\pi^0 \rightarrow \gamma + \gamma$$

Chiral anomaly speeds up decay by a factor 3×10^8 !
Earliest (?) hint of 3 colors

u u u



Adler-Bell-Jackiw anomaly

Spoiler role in chiral gauge theories
Ruins chiral charge conservation and renormal.
Topological in origin

$$\nabla . \mathbf{J_5} + \frac{\partial \rho_5}{\partial t} = W$$

Anomaly-free condition
In a chiral theory, *all* the anomalies must cancel for it to be renormalizable.
This imposes stringent constraints, e.g. number of generations.
In Glashow-Weinberg-Salaam theory, exact cancellation involving 10+ diagrams has been called “magical”.

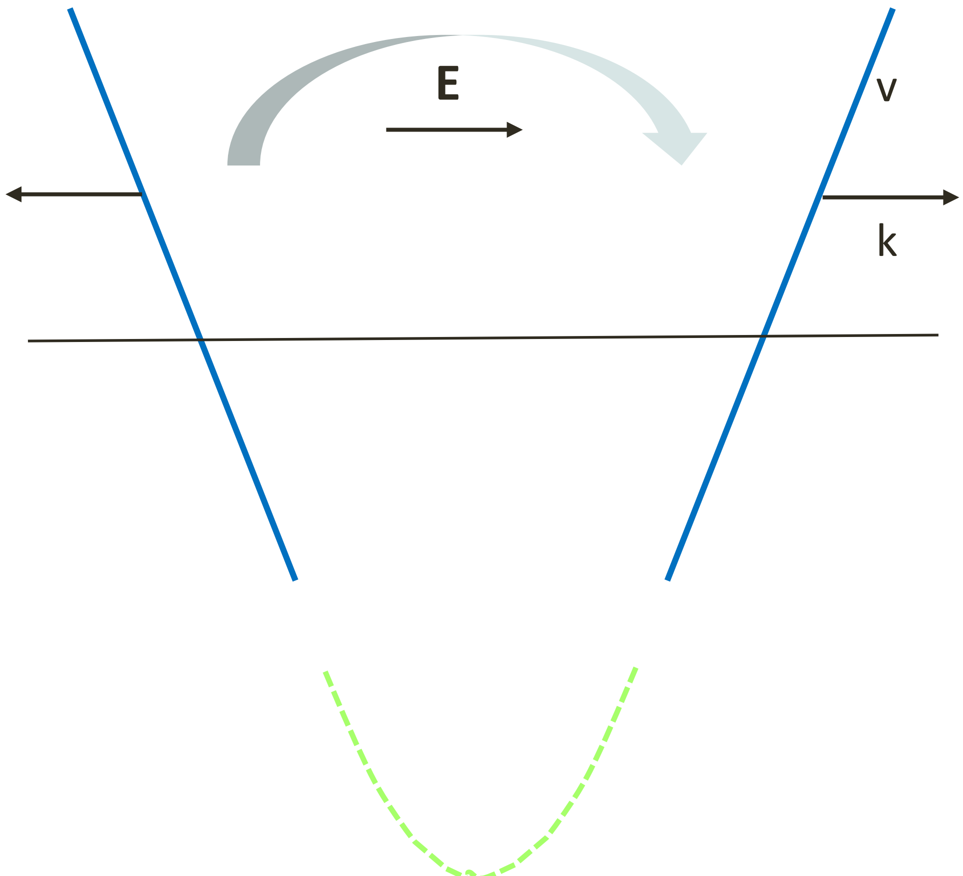
Nielsen and Ninomiya (*Phys. Lett.* 1983) proposed chiral anomaly may be observable in *(1+1)d* or *(3+1)d* crystals ---- *even* spacetime dim.

Detecting the chiral anomaly in a crystal?

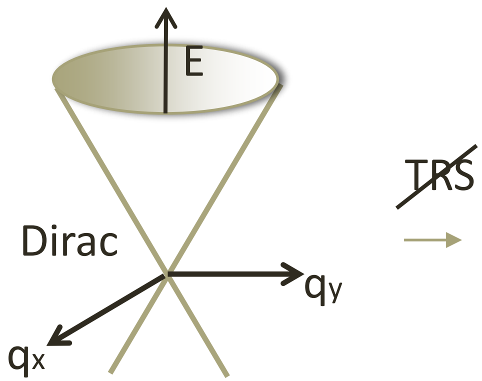
Nielsen and Ninomiya (*Phys. Lett.* 1983)

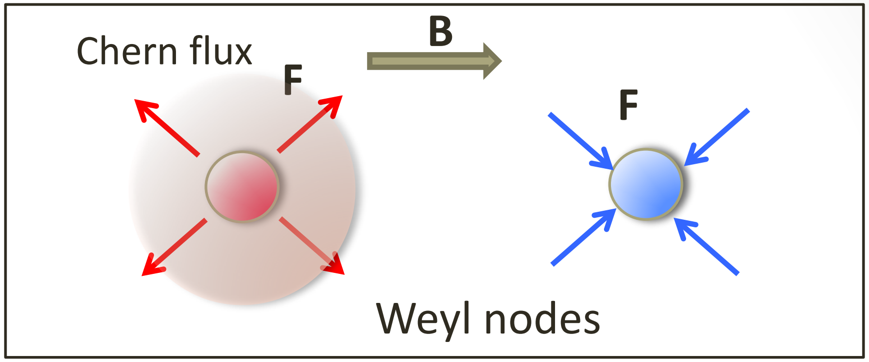
For massless Dirac fields, the natural repres. is chiral (Weyl) representation.
However, coupling to EM fields breaks chiral symmetry.

$$i\gamma^{\mu}\partial_{\mu}\Psi = 0$$



TRS breaking splits Dirac node into 2 Weyl nodes





Berry curvature $\mathbf{F}(\mathbf{k}) = \nabla_{\mathbf{k}} \times \mathbf{A}(\mathbf{k}),\quad \mathbf{A}(\mathbf{k}) = i(u_{\mathbf{k}}|\nabla_{\mathbf{k}} u_{\mathbf{k}})$

- Weyl nodes come in pairs with $\chi = \pm 1$
- Acts as monopole source or sink of Berry curvature **F** (or Chern flux Φ)

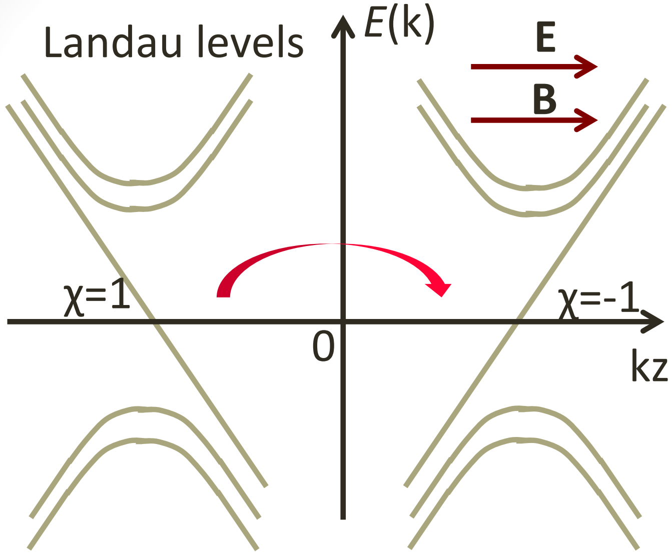
$$\chi = \frac{1}{2\pi}\oint \mathbf{F}(\mathbf{k}).\,\mathrm{d}\mathbf{S}(\mathbf{k})$$

Non-conservation of chiral charge in *E* field → the chiral anomaly

Wan, Turner, Vishwanath, *PRB* 2011
Burkov, Hook, Balents, *PRB* 2011
Son, Spivak, *PRB* 2013

… and 80+ theory uploads on arXiv

Charge pumping and the chiral anomaly



Nielsen, Ninomiya, *Phys. Lett.* 1983
Wan, Turner, Vishwanath, *PRB* 2011
Burkov, Hook Balents, *PRB* 2011
Son, Spivak, *PRB* 2013
Parameswaran et al. *PRX* 2014
Hosur and Qi, *Comp. Rend. Phys*. 2013

Chiral anomaly engenders large, negative longitudinal MR *Locked* to B field

In large-*B* regime, with **E||B,** charge is pumped between Weyl nodes at the rate

$$W = -\frac{L^2}{2\pi\ell_B^2}\frac{Le\dot{k}}{2\pi} = -V\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}.\mathbf{B}$$

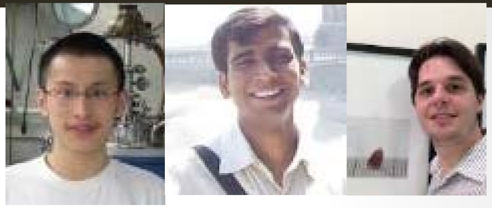
In weak *B*, charge pumping gives (Son and Spivak, *PRB* 2013)

$$\sigma_\chi = \frac{e^2}{4\pi^2\hbar c}\frac{v}{c}\frac{(eBv)^2}{\epsilon_F^2}\tau_v,$$

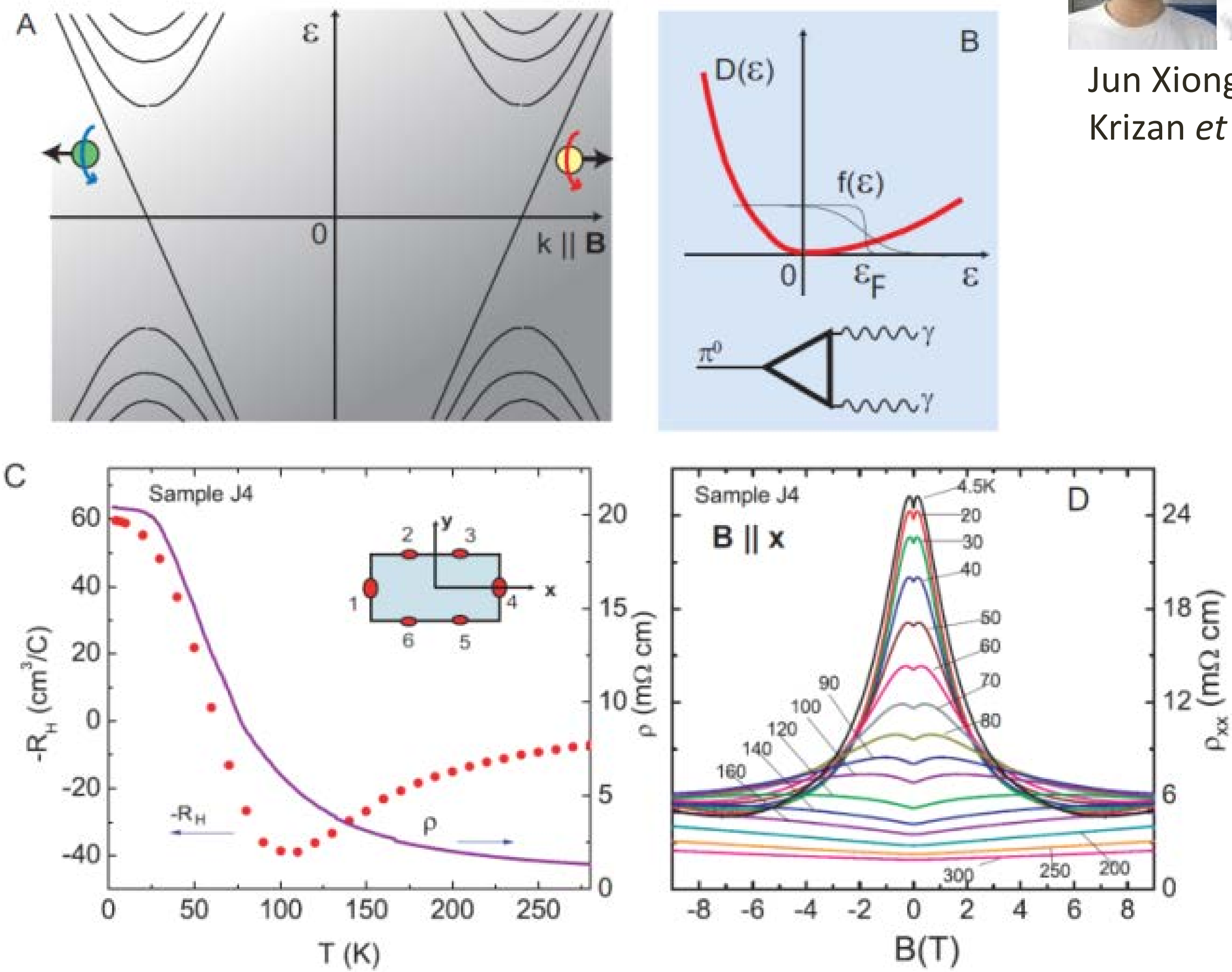
τ_v is intervalley scattg time

Non-metallic resistivity and negative longitudinal MR in Na_3Bi

Long-term annealed crystals with E_F ~ 30 mV

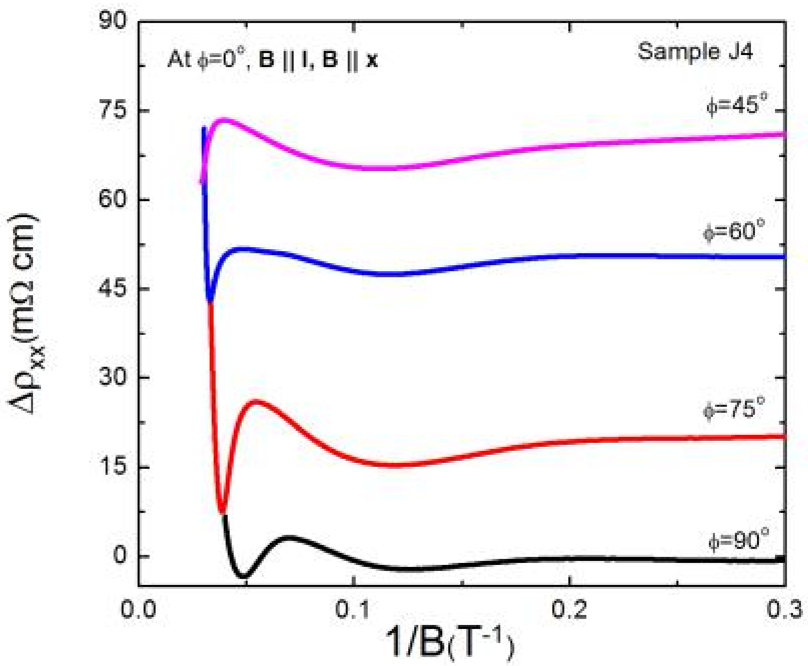


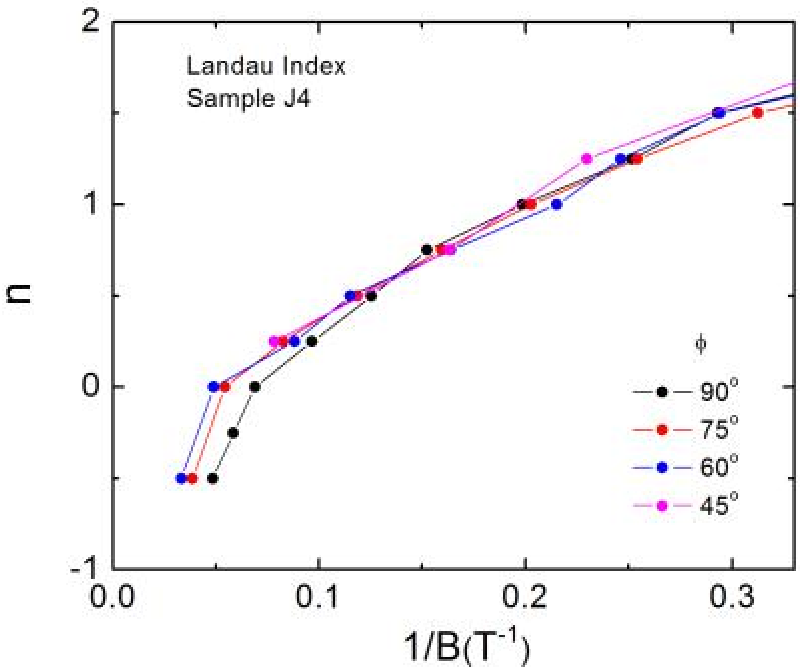
Jun Xiong, S. Kushwaha, Krizan *et al.*, submitted



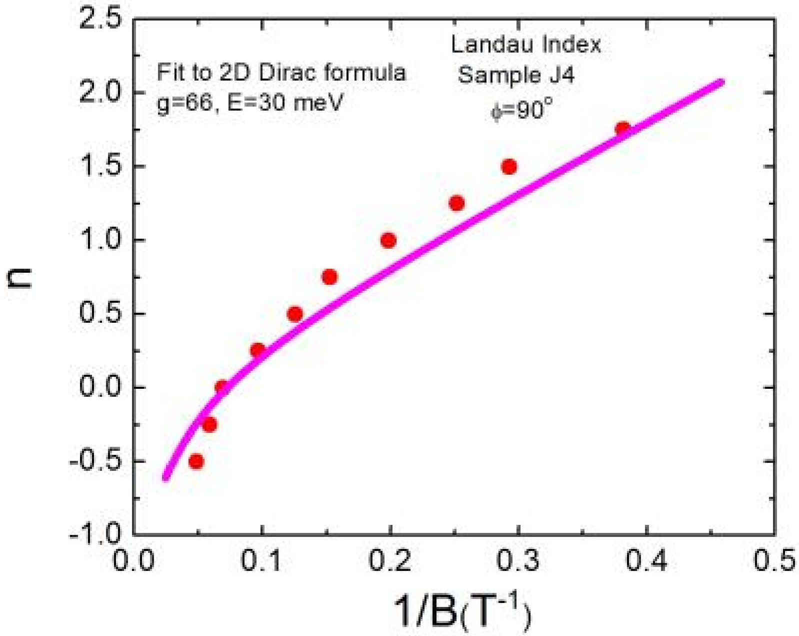
Extremum of RH implies a Fermi energy of 30 meV above node

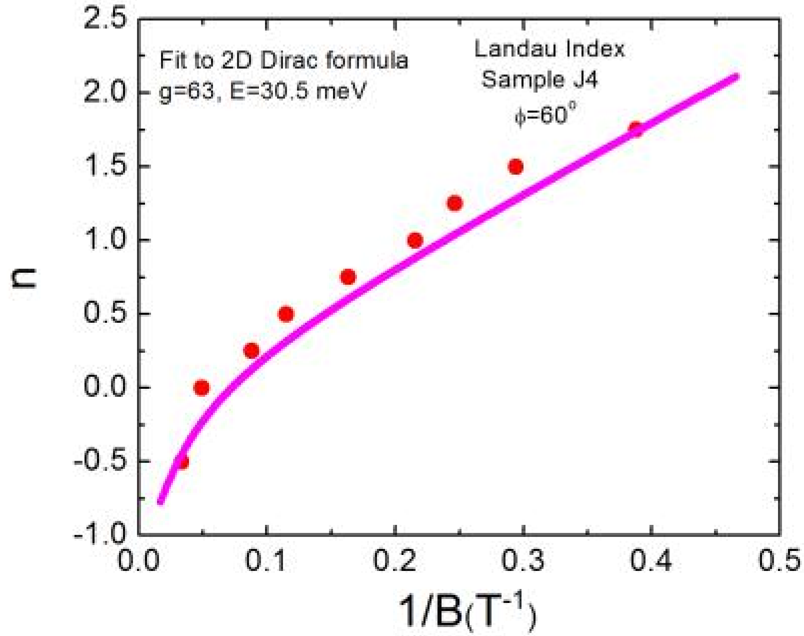
Approaching n=0 Landau level





Evidence for a very large g factor (~63)



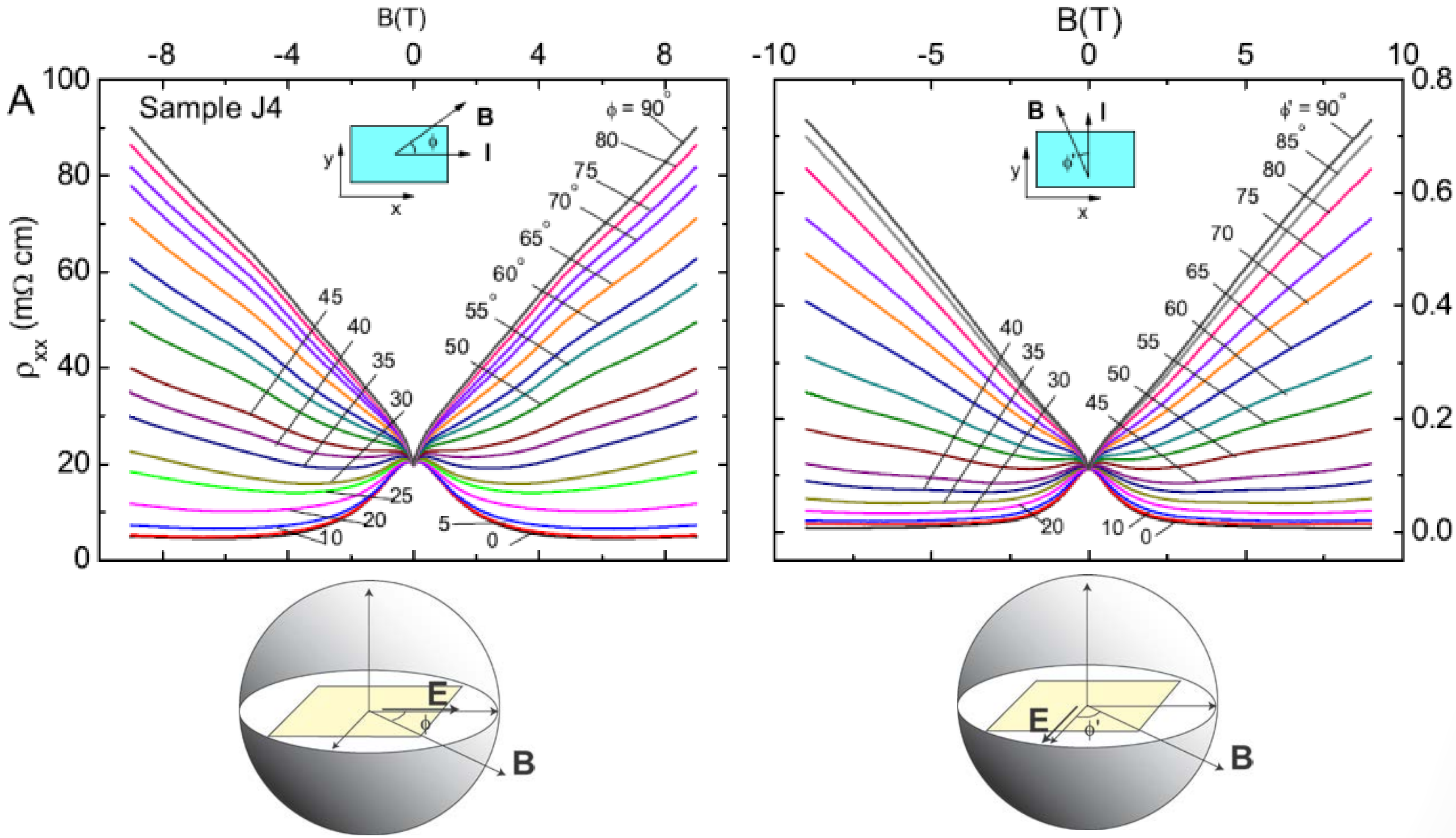


A very large deviation from straight line observed in index plot

Poor-man's fit yields E_F = 30 mV, g ~ 63

A crucial test for chiral anomaly -- **B** is locked to **E**

Jun Xiong, S. Kushwaha et al., submitted



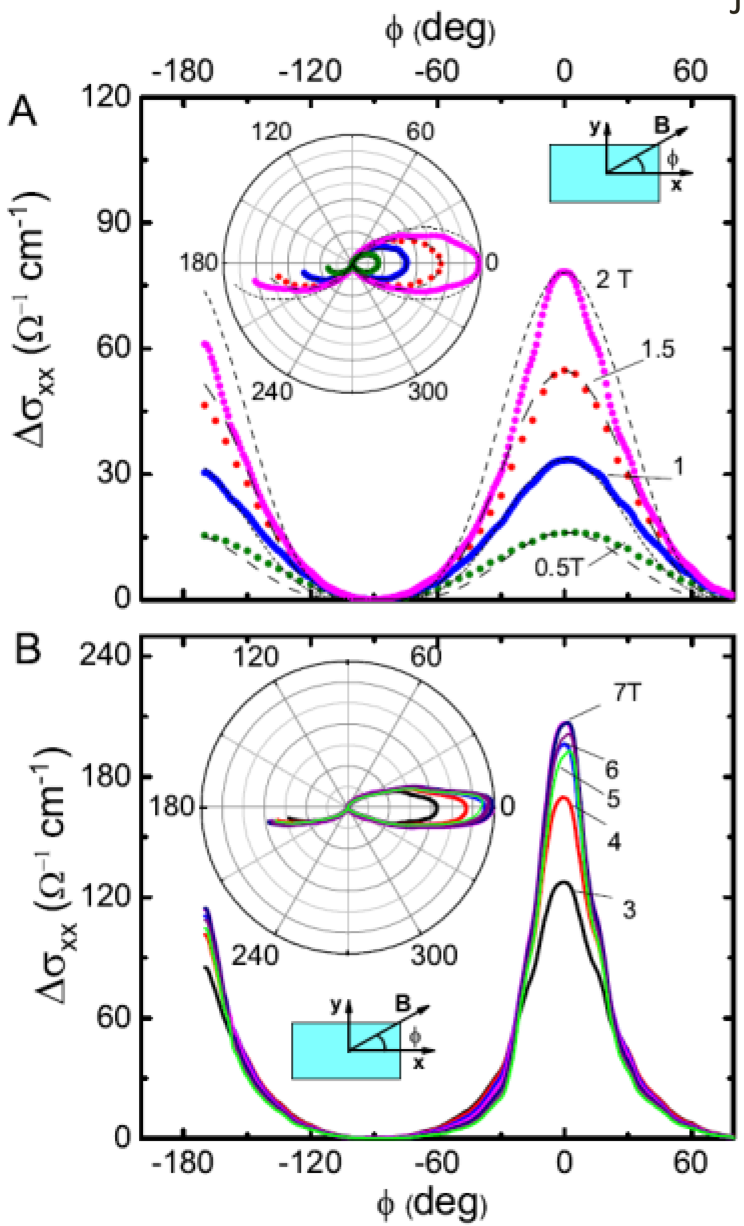
Negative MR appears only when **B** is locked to **E.**

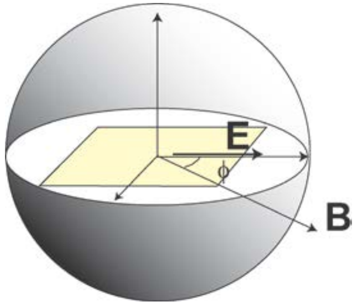
Test: if **E** is rotated by 90^o (right panel), neg. MR shifts to new direction of **E.**

For weak B, this locking is novel and unexpected in semiclasscl transport

A narrow plume of chiral current, B in-plane

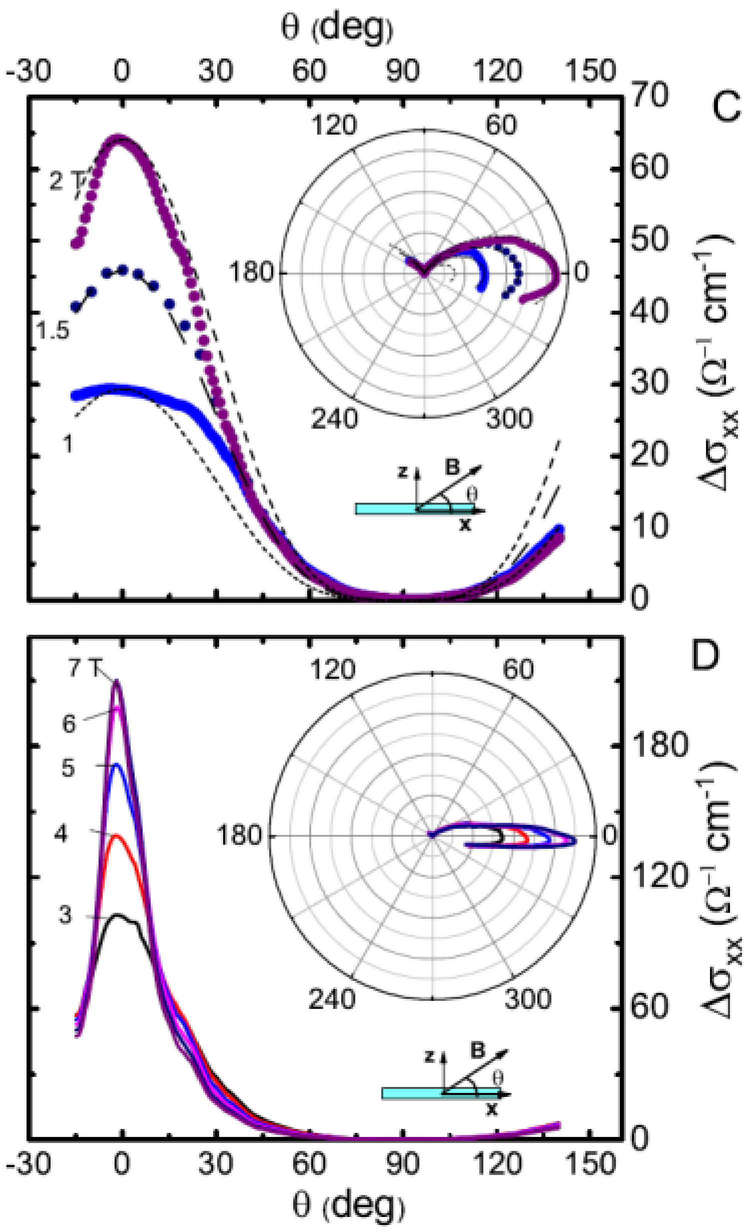
Jun Xiong, S. Kushwaha et al., submitted

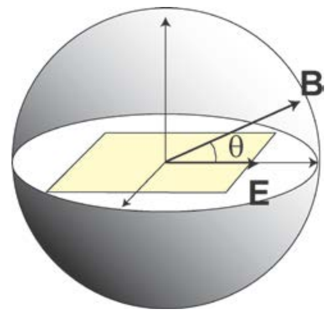




Enhanced cond. in a narrowly collimated beam for **B** in the *x-y* (horizontal) plane

Width of chiral conductivity "plume", B normal to plane

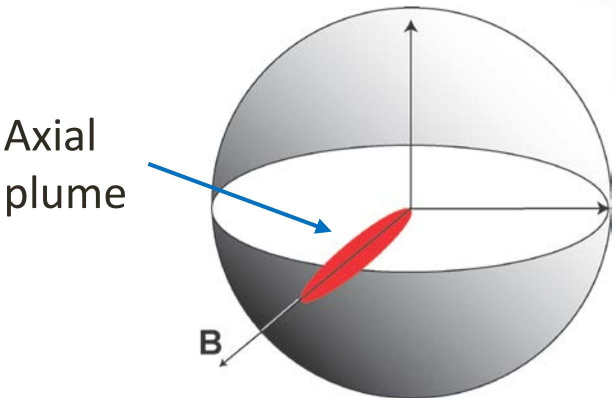




Enhanced cond. in a narrowly collimated beam for **B** rotated in the *x-z* (vertical) plane

Signature of chiral anomaly: **B** locks direction of axial current

In conventional transport, we cannot “rotate” FS parameters, e.g. scattering rate anisotropy, by rotating direction of a weak **B**.

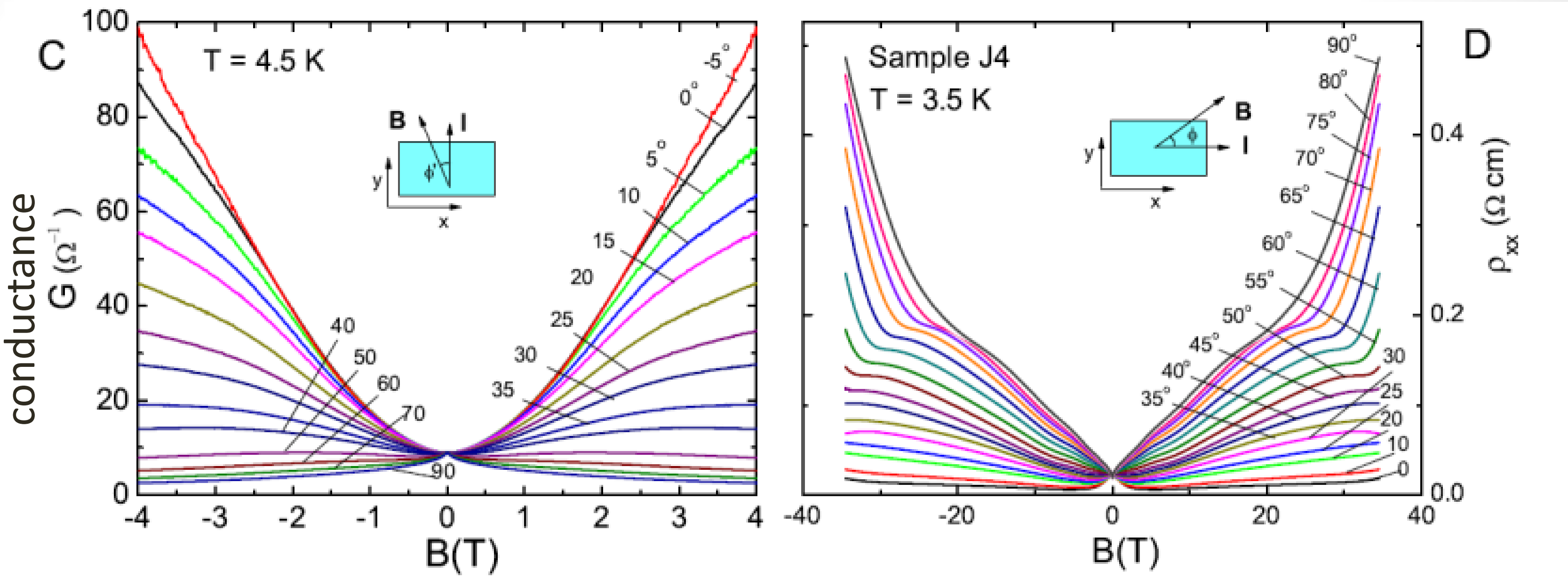


Locking of observed axial to **B** (even in *weak B*) seems to be a signature characteristic of the chiral anomaly.

Axial plume direction fixed by **B** (and **E**)

Observation of negative, longitudinal MR is necessary but insufficient.

Determine intervalley scat. lifetime using Son-Spivak expression



$$\sigma_\chi = \frac{e^2}{4\pi^2\hbar c}\frac{v}{c}\frac{(eBv)^2}{\epsilon_F^2}\tau_v,$$

In semiclassical regime, Weyl node conductivity grows as B^2 (Son, Spivak, *PRB* '13)

From fit, we find τ_v = 40-80 τ_0

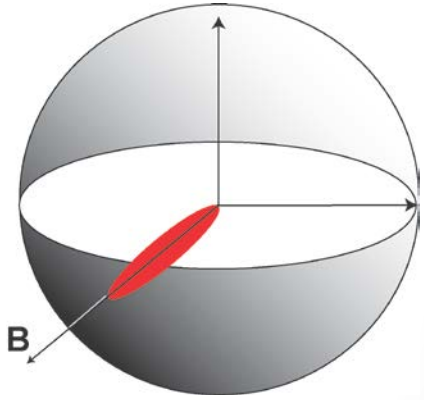
Summary

Transport experiments on Dirac semimetals

In Cd_3As_2, we observe very high mobility (9 million cm^2/Vs) in zero *B*. Appears to be protected by a zero-*B* mechanism. Giant MR observed when protection is lifted.

In Na_3Bi, in samples with E_F ~ 30 mV, we see evidence for the chiral anomaly.

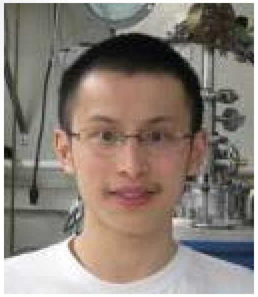
Signature: The enhanced-conductivity "plume" is locked to the direction of **B** (and **E**). **YES**



Estimated inter-valley lifetime is 40-80 x longer than Drude value.

A surprise: Width of plume is *much narrower* than anticipated by theory.

End



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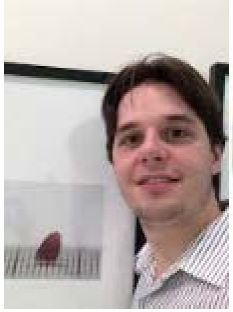

Jason Krizan

Quinn Gibson

Bob Cava

NPO

Thank you

References:

1) ''Signature of the chiral anomaly in a Dirac semimetal: a current plume steered by a magnetic field,'' Jun Xiong, Satya K. Kushwaha, Tian Liang, Jason W. Krizan, Wudi Wang, R. J. Cava, N. P. Ong. arXiv:1503.08179

2) "Evidence for the chiral anomaly in a Dirac semimetal,'' Jun Xiong, Satya K. Kushwaha, Tian Liang, Jason W. Krizan, Max Hirschberger, Wudi Wang, R. J. Cava, N. P. Ong, submitted.